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International Trade and Energy Intensity During European Industrialization, 1870–1935

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ABSTRACT

Previous research suggests that there is an inverted U-shape curve for energy intensity in the long-run for Western Europe with a peak in the early 20th century. This paper tests the hypothesis that the increase of German and British energy intensity was an effect from the concentration of heavy industrial *production* to these countries, although the *consumption* of a significant share of these goods took place elsewhere. We use an entirely new database that we have constructed (TEG: Trade, Energy, Growth) to test whether these countries exported more energy-demanding goods than they imported, thus providing other countries with means to industrialize and to consume cheap-energy demanding goods.

We find that the U-shape curve is greatly diminished but does not disappear. The pronounced inverted U-curve in German energy intensity without trade adjustments is reduced when we account for energy embodied in the traded commodities. For Britain the shape of the curve is also flattened during the second half of the 19th century, before falling from WWI onwards. These consumption-based accounts are strongly influenced by the trade in metal goods and fuels, facilitating industrialization elsewhere.

1. Introduction

Today, China is often perceived as the workshop of the world, producing large amounts of cheap consumer goods for others. A century ago Britain and Germany (along with the United States) played a similar role both for Europe and globally. In these 'workshops of the world' energy and other resources are used to produce goods to satisfy foreign demand. This means that national levels of energy consumption may look profoundly different when international trade is taken into account and energy use is attributed to the final consumer, rather than producer of a good: the so-called consumption based approach (Davis and Caldeira, 2010), or ecological footprint approach (Wackernagel and Rees, 1996). Calculating consumption-based environmental impact has become popular but only covers recent decades. Often the consumption-based approach focuses on the patterns and levels of consumption of individuals.

However, from a national perspective 'consumption' is defined as production minus exports plus imports. Often contemporary consumption-based studies draw the conclusion that the developed world is outsourcing energy intensive and environmentally damaging production abroad (Peters et al., 2011). However this can be questioned. Some of what appears to be the displacement of emissions from the developed to the less developed countries is an illusion, caused by trade between nations with energy systems of differing levels of carbon intensity, and/or levels of energy efficiency. An improvement in energy efficiency in a developed nation, for example, could appear to be a relative 'outsourcing' of environmental damage to a developing nation without any actual alteration in trade. Yet this is hardly outsourcing as commonly understood (Jakob and Marschinski, 2012; Kander et al., 2015). Furthermore, if earlier growth in consumption levels across much of the world depended on high levels of consumption of energy by the historical 'workshops', this argument is reversed for the past: Britain and Germany were providing the rest of the world economy with cheap coal and steel, while suffering pollution and resource depletion.

The main objective of our paper is to understand the nature of nations' energy needs over different phases of their historical development. The means for achieving this objective is to explore if, and how, the energy intensity curves for-7 European countries change from 1870 onwards when measuring energy use from the trade-adjusted consumption side, instead of attributing energy use solely to the point of combustion.

A standard way to measure the relationship between economic development and energy use is through energy intensity (EI), the amount of energy required to produce a unit of GDP. It has been argued that material resource use and pollution both increase, at least in relative terms, i.e. in relation to GDP, during industrialization and decline as the nations mature into service-oriented countries (Panayotou, 1993). This argument is formalised as the Environmental Kuznets Curve (EKC). It

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implies that in the course of development things need to get worse before they can get better. Another implication drawn from this argument is that economic growth tends to solve its own environmental problems, at least in relative terms. The economy becomes less demanding of natural resources and less polluting in relation to the value of output it creates. In reality the interrelations of the economy and the environment are more complex. As demonstrated in a World Bank Report of 1992, while certain environmental damages tend to gradually diminish over time as incomes rise, such as smoke pollution, others show continuous increases, such as the volume of garbage. Other impacts are not easily measured, such as biodiversity or ecosystem quality. An additional problem is that some authors have mistaken relative decoupling of environmental impact and GDP with absolute decoupling (Radetzki, 1990) and erroneously drawn the conclusion that if the pollution per unit of GDP goes down, then the environment is less pressured overall. This is of course not true: if the scale of the economy grows faster than the rate of delinkage of energy consumption and growth, then absolute environmental pressure will increase. The lion's share of EKC studies deal with absolute environmental pressure or emissions in relation to income levels, but there are some examples where pollution intensity is addressed instead (Sun, 1999; Tan et al., 2015). One can therefore distinguish between a weak and strong hypothesis for the EKC, where the weak hypothesis only suggests that pollution intensity resembles an inverted U (Blackwood, 2002:124–126).

Reddy and Goldemberg (1990) proposed the idea of a similar inverted-U curve for energy intensity, although its is important to note that this is not identical with the EKC even in the case of the weak hypothesis (pollution intensity), as different energy carriers pollute to a very different degree (compare windpower with coal, for example).[1]

The existence of such a curve for energy intensity with the same shape for all countries, only differing in the timing and level of the peak, would suggest a universal pattern of industrialization, even though latecomers can learn from pioneers and by the use of more efficient technologies and peak at a lower level. Such a model suggests that all countries go through a period of increasing energy intensity as they industrialize. Previous research has not entirely confirmed this picture. Our earlier research has demonstrated that the inverted-U curve does not hold for a number of European countries, where energy intensity actually falls over the long period 1800 until today, if we include both traditional and modern energy carriers in the picture (Gales et al., 2007; Kander, 2002). In these studies imports of coal and other fossil fuels are included in national energy consumption, and direct exports of such fuels (such as coal from England and Germany) are deducted from their energy consumption. However, the embodied energy in goods consumed elsewhere is not adjusted for in these calculations. It was found that the inverted U-curve of energy intensity holds for the UK and Germany, and their share of total European GDP and energy consumption was so large that the whole continent's energy intensity also followed an inverted U-shape (Kander et al., 2013).

In this article we critically revisit the inverted U-curve for energy consumption. Could it even be the case that there was no such curve for Europe when energy embodied in international trade is taken into account, that is, when we employ a consumption-based measure? This would indicate that the inverted U-curve is not associated with rising incomes and a stage of development per se, but the concentration of energy intensive activity in particular countries or regions. Perhaps Germany and Britain were exporting so much energy embodied in goods in the 19th century to countries outside the continent that European energy intensity, from a consumption perspective, may have been stable or even fallen during industrialization? This is not entirely improbable. The period 1800–1913 saw a rapid expansion in world trade: from 3% to 33% of world production. Europe made up 62% of world trade in 1913 and mainly exported manufactured goods and imported primary goods (Kenwood and Lougheed, 1992). Manufacturing exports were dominated by the UK (which sold 70% of its exports to non-European countries in 1913) and Germany (selling 34% of their exports outside Europe) (Svennilson, 1954). We will examine whether the inverted U-curve for energy intensity ceases to exist for Britain and Germany (and thus for Europe) when their international trade is accounted for. Equally, will we find countries whose energy consumption appears considerably higher once imported goods are brought into the picture? Our analysis covers seven countries: the UK, Germany, the Czech lands, Denmark, Sweden, Italy and Portugal, over the time period 1870–1935.

Section 2 of the article discusses previous research on long-term energy intensity, where this has not been adjusted for energy embodied in traded goods. Section 3 describes the new dataset that we have constructed, and how it relates to similar approaches by other researchers. We also provide a more extensive document of supplementary information (SI) alongside this paper, describing in far more detail the methods employed and results obtained, in particular on how the energy embodied in particular traded commodities has been calculated. Section 4 presents the overall results for our set of countries, firstly on energy embodied in traded commodities, both imports and exports, and secondly on how energy intensity changes after trade-adjustment. The discussion in Section 5 evaluates the implications of our results for the wider understanding of long run energy history.

2. Previous Research on Long Term Energy Intensity

Previous work has already demonstrated that Reddy and Goldemberg (1990) overestimated the upwards slope of energy intensity during industrialization because they did not include traditional energy carriers such as wood and draft animal power. Initial levels of energy consumption were much higher than they appreciated. European countries that did not have access to large domestic deposits of coal, such as Sweden, the Netherlands, Italy and Spain, all showed either a slowly or even drastically declining energy intensity curve over time (Gales et al., 2007). Analyses of Canada and the United States have also shown drastically declining energy intensity during the 19th century (Csereklyei et al., 2016; Henriques and Borowiecki, 2017; Unger and Thistle, 2013). These results disproved the existence of a uniform inverted U-shape curve for all countries. Nevertheless it remained the case that some countries endowed with large deposits of domestic coal, primarily Britain and Germany, do show increasing energy intensity during their industrialization (Kander et al., 2013; Warde, 2007). In Britain's case this upward shift began early, as coal became the dominant fuel during the seventeenth and eighteenth centuries (Malanima, 2016; Warde, 2007). Since they were such large economies and took an increasing share of the continent's economic activity, their pattern affects the aggregate western European picture which thus also becomes an inverted U-shape curve.

Fig. 1 presents both the aggregate curve of energy intensity since 1820 for the eight Western European countries that were covered by our previous research, and a stylized inverted U-shape graph based on this.

In this article for reasons of data availability we use a different sample of countries but the shape of the curve, still driven by Britain and Germany, is very similar (see Fig. 2).[2] Although we have not been able to

[1] Due to the non-proportional relationship between energy and environmental pressure as some energy carriers are polluting and others are not, and due to the possible confusions between the weak and strong EKC hypothesis, we refrain from the use of the EKC concept entirely, when we speak about energy intensity and instead use "the inverted U-curve." The ideas that structural change (industrialization, service transition) explains the shape of the curve are however the same for both EKC and energy intensity.

[2] The advantage with using this sample throughout the rest of this paper is that we can aggregate the national figures of energy embodied in imports and also aggregate the energy embodied in exports and get a grand total net balance for our combined set of countries. We can then see how much it can alter the aggregate shape of the European energy intensity curve for exactly this sample of countries. For this purpose we do not need to know exactly how this trade was distributed between these countries (i.e. the precise flows between each other); we only need to know what were the inflows and outflows for the whole of our sample, as any intra-sample trade cancels out.

Fig. 1. Graph of European aggregate energy intensity, 1820–2009, MJ per constant international dollar, 1990 price level.
Source: Kander et al. (2013) based on 8 countries: Britain, Germany, France, Italy, Spain, Netherlands, Sweden and Portugal.

include France, Spain and the Netherlands, we have added Denmark (Henriques and Borowiecki, 2017; Henriques and Sharp, 2016) and the Czech lands (Nielsen et al., 2016). Having access to data for the Czech lands is especially interesting, since it is a coal-rich eastern European country.

Fig. 3 shows the energy intensities of the same seven individual countries included in the sample for the aggregate curve in Fig. 2 for the critical period 1870 to 1935, when the aggregate curve peaks and begins to fall. We see that as well as Germany the Czech lands had an inverted U-shaped curve for energy intensity, increasing from 1870. As mentioned above, Britain's energy intensity had already begun rising prior to 1800, peaking in the 1870s. The other economies, without domestic coal, had either flat or decreasing energy intensity during the period.

Energy intensity can change for various reasons; technical change, structural change, and changes in energy quality. Changed patterns of international trade may induce structural change. Structural change in economies means that the relative role played by different sectors in creating GDP varies over time. As nations industrialize their manufacturing grows relatively faster than agriculture, for example. Sectors differ in

Fig. 2. Energy intensity of Britain, Germany, Czech lands, Denmark, Sweden, Italy and Portugal 1800–2000, MJ per constant international dollar, 1990 price level. Source: our construction with the data from Henriques (2011); Kander et al. (2013), Henriques and Borowiecki (2017), Henriques and Sharp (2016), and Nielsen et al. (2016).

their energy requirements; to take a simple example, it takes more energy to produce $1000 worth of steel than of pills. Technical or within-sector change in the efficiency of energy use will reduce overall energy intensity, ceteris paribus. However if at the same time structural change shifts the balance of economic activity towards more intense sectors, then this countervailing force would still cause overall energy intensity to rise. Thus even as the industrial sector improves its own technical (within-sector) efficiency, its relative growth can push aggregate energy intensity up. The relative roles of structural and technical change are very important in the analysis of energy intensity, as has been found for studies of contemporary nations (Fujii and Managi, 2013; Mulder, 2015; Voigt et al., 2014).

Energy quality distinguishes energy carriers according to the differential uses to which they can be put; electricity is much more versatile than coal or draft animal power, for example. This can be analysed through prices, which must to some degree reflect these differences (Cleveland et al., 2000; Stern, 2010). Considering energy quality is especially relevant for the period when oil and electricity enter the scene on large scale, i.e. in the second half of the 20th century in Europe. Gentvilaite et al. (2015) explored the role of energy quality in shaping long-term energy intensity for Britain and Sweden, based on national energy retail prices. No relation was identified between energy quality and energy intensity in the 19th century, while improved energy quality may have stimulated declining energy intensity in Europe over the 20th century.

Other potential sources of explanations for the drastic decline in energy intensity observed after 1970 are the effects of the oil crises in the 1970s, which may have stimulated both technical change, and the structural effects of deindustrialization and transition towards a service economy. While the service transition is largely a price illusion when it comes to structural changes in the actual physical production of societies (as opposed to the distribution of the workforce), it has exercised some influence on energy intensity change as shown by conventional decomposition analysis (Ang and Zhang, 2000; Henriques and Kander, 2010; Kander, 2005). More generally recent work suggests that the core innovations of the third industrial revolution (such as the microprocessor) played a greater role for reducing both material and energy intensities from the 1970s (Fischer-Kowalski and Amann, 2001; Kander et al., 2013; Krausmann et al., 2009; Wiedenhofer et al., 2013).

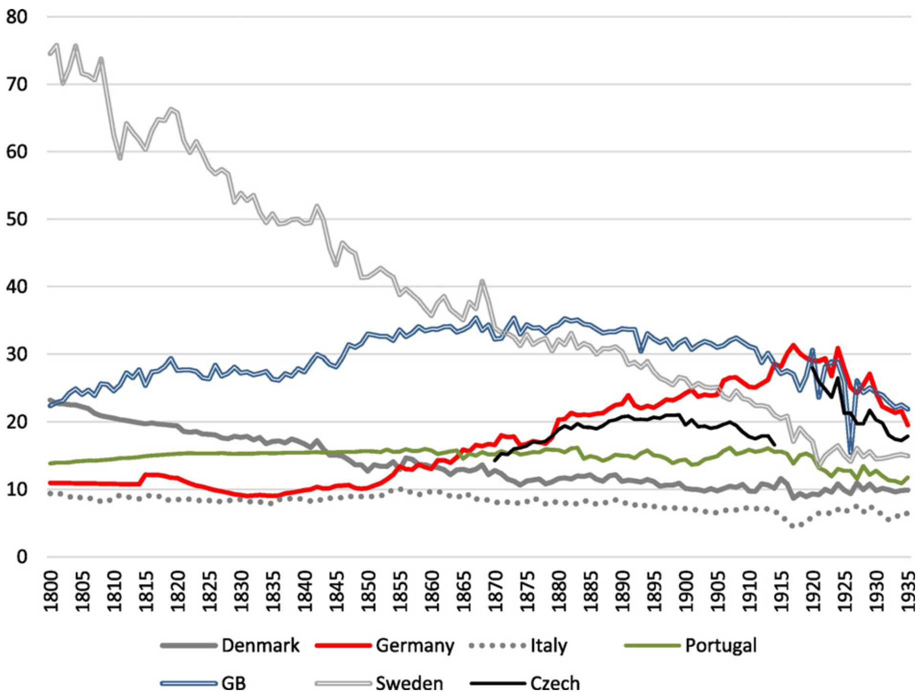


Fig. 3. Individual country trends, energy intensity, (MJ/$1990), 1800–1935.
Sources: For Portugal: Henriques (2011), For Denmark: 1870–1913 Henriques and Sharp (2016), 1914–1935 Henriques and Borowiecki (2017). For the Czech lands, Nielsen et al. (2016). For the other countries: Power to the People, Kander et al. (2013). Swedish energy intensity is revised from the book 'Power to the People' as new research has shown that firewood use for charcoaling in the iron industry was substantially higher than assumed in previous estimates by Schön (1992).

Energy intensity can also be indirectly affected by international trade via structural change. If a country specializes in heavy industrial goods for export it is likely to have a high energy intensity. If part of the decline in energy intensity in Europe after 1970 was due to the displacement of emissions to less developed parts of the world through trade, this may be a matter of moving the resource and environmental problems rather than solving them. For the period of industrialization in Europe during the 19th century, decomposition analysis clearly demonstrates that increasing energy intensity was driven by structural change with industry gradually taking up a larger fraction of GDP in at least the UK and Sweden, countries where we have established sectoral energy intensity data (Kander et al., 2013, Appendix B). This was almost certainly true for Germany as well. This paper addresses whether part of this structural change was due to international trade.

3. Methods and Data

This work relies on a new database, TEG (Trade, Energy and Growth), which will be linked to the LEG (Long-run Energy and Growth) database previously published online (used in Kander et al., 2013; see www.energyhistory.org).[3] LEG is constructed from a conventional 'production' perspective, that accounts for the energy used within national borders (and thus includes imports and exports of energy carriers such as coal and oil, but no embodied energy). TEG provides a consumption-based account of energy instead, and contains information about quantities of exported and imported goods for all our countries where these are relevant for an energy analysis; the amount of embodied energy in these traded goods; and the net result of embodied energy flows. This allows the calculation of consumption-based energy account and we include in this study the benchmark years ca 1870, 1913 and 1935. Data is provided for Germany, Great Britain, Sweden, Portugal, Italy, Denmark and the Czech lands.[4]

Energy sources included are primary energy carriers, both traditional and modern. Traditional energy sources are firewood, feed for draft animals, and direct working water and wind (the latter being very small shares of the total).[5] Modern carriers include fossil fuels (coal, oil and later natural gas), and electricity produced from sources other than fossil fuels: hydro, nuclear, wind, solar etc.[6]

Our approach has much in common with studies of material flows, and industrial and social metabolism (Ayres and Simonis, 1994; Cussó et al., 2006; Fischer-Kowalski and Hüttler, 1998; González de Molina and Toledo, 2014; Haberl et al., 2001; Krausmann et al., 2009; Kuskova et al., 2008). All are interested in the interaction of human societies and their environmental and ecological context over time, and especially the transformations brought by industrialization and globalization. Such approaches have sought to develop an understanding of such relationships and changes through the mapping of quantitiative flows of

[3] This covered Germany, Great Britain (Warde, 2007), Sweden (Kander, 2002), France, Portugal (Henriques, 2009, 2011), Italy (Malanima, 2006), Spain (Gales et al., 2007) and the Netherlands (Gales et al., 2007).

[4] For the Czech lands, all data prior to WWII refer to Czech lands only, thus the geographical area which more or less corresponds to the current territory of the Czech Republic. Within the period of 1870–1913, the Czech lands were a part of larger entity – the Austro-Hungarian Empire. For the period after WWII, the geographical scope includes the newly created republic of Czechoslovakia, thus both the Czech and Slovak Republic. German data refers to what were its current borders at the time, as some territory was lost after 1919. British data refers only to Great Britain and does not include Ireland, although the Irish Free State was part of the UK before 1921 and Northern Ireland remained in the UK throughout the period.

[5] Food for humans was not included, since this is not done in contemporary consumption-based acccounts. It would require a full account of labor time used in different production processes as well as estimates of how large share of a worker's food that was consumed while he was working. Moreover rough calculations we have made including the labor force make it clear that it would comprise a very small share of the energy embodied in traded goods.

[6] We do not quality-adjust the energy on basis of prices, and nor do studies of Energy Intensity or embodied energy in general. Of course different carriers do have varied qualities, although the most distinctive, oil and especially electricity, did not have very wide usage during this period. Coal, having a higher energy density, was better for transportation than firewood, but in many regards they are not dissilimar.

matter, nutrients and energy, establishing an idea of what the basic material and energy needs for particular phases of development have been and how they have been met. However, our method differs in important ways. In calculating energy embodied in traded goods we do not only count direct energy used in the final stage of production, but also indirect energy used in earlier stages of production to extract and manufacture the main inputs into the final commodity. This is a major difference between our method and previous physical balance of trade (PBT) analyses applied to historical data, such as Krausmann (2015) or Schandl and Schulz (2002). Our approach is in this respect more similar to energy accounts introduced by Odum (1995) (Hau and Bakshi, 2004), but differs in that we do our calculations in terms of fuel equvialents, rather than equivalents of solar energy, and we draw narrower boundaries around the production system. Our focus on energy as a strategic resource, following the chain of production of goods and all related energy inputs through a detailed process analysis means that we can thus trace not only the direct exchange of fossil fuels and strategic resources like steel and cotton, but also the "hidden" or embodied flows of energy. More localised studies have provided such historical information for some agricultural commodities (Aguilera et al., 2015; Tello et al., 2016) we provide estimates for national trade as a whole. We view all these different approaches as complementary in seeking to understand the intertwined story of social metabolism of societies and their energy histories; but it is important to recognise that different studies do not measure precisely the same things.

The ecological footprint approach (Wackernagel et al., 2004; Wackernagel and Rees, 1996) is also closely related to studies of social metabolism. It translates all feasible environmental impacts into land equivalents, and by including embodied land in products, bridges over to the contemporary studies of embodied energy and carbon emissions, called the carbon footprint or consumption-based carbon accounting. This form of consumption-based accounting is conducted on basis of large world wide input-output databases from the 1990s onwards, tracing the energy and carbon emissions upstreams in the global value chains of production. However this has not been attempted for earlier periods (Lenzen et al., 2012; Peters et al., 2011; Wiedmann et al., 2015).

In the Supplementary information (SI) to this article we lay out in detail our methods and provide the sources of information for the individual countries and products. The basic method we use to trace energy embodied in goods is process analysis (Bullard et al., 1978), and the relationship of our method to process analysis and the more well-known life-cycle analysis is also set out in the supplementary material. The constraints of historical data means that energy inputs into production have to be reconstructed step by step from a range of sources, but with extensive use of industrial censuses. As explained in the SI, we do not include the energy required to produce capital goods (e.g. machinery) used for the productive processes we examine, although the production of new machinery is included. The scale of this task means goods covered have been limited to those estimated to require energy inputs of a signficant scale in traded goods (some goods may be relatively energy intensive but are not traded internationally, such as bricks). For examples of how technical coefficents and multipliers are constructed for certain key products, please see the SI.

In applying process analysis to historical data, we establish the main steps in the production of a final good and add energy consumption figures at each step to produce an aggregate total. In process analysis this total is called the multiplier, that is the amount by which a basic unit of the good should be multiplied to reach the figure for embodied energy. Our calculations use a multiplier of GJ per ton. For instance the production of simple iron and steel goods contains three main steps: 1) mining ore 2) reducing the oxygen of the ore and refining it into pig iron 3) smelting and working the metal into final products. Steps 2 and 3 are the most energy consuming and have the highest energy requirements (energy needed to produce one ton of output). The energy used in the final step in the production is called the *direct* energy requirement, while the energy used in producing inputs into the final step in production is called the *indirect* energy requirements. The multiplier is the sum of the indirect and direct requirements per unit of final output. The different steps also produce waste, as well as by-products to which, in certain circumstances, energy inputs should be allocated. A ton of final good may require more or less than a ton of each input (for example, one ton of cotton goods required 1.08 tons of raw cotton because of wastage in production). Thus the indirect energy requirement for each ton of input into a final good must be adjusted to reflect this using a ratio of input weight to the weight of final product called the technical coefficient, raw cotton having a coefficient of 1.08.

Creating the TEG database requires three steps.

3.1. Energy Requirements and Multipliers

Firstly we must find information on the energy required to produce goods, that is, to establish all of the indirect and direct energy requirements that allow calculation of the multiplier for each ton of traded product. The limiting factor is detailed data on energy use. In contrast, trade statistics are the most widely available historical statistics, often with very detailed annual data for both imports and exports. Logically this implies that the system for identifying homogeneous product groups for which multipliers can be established must be driven by the available energy data rather than the trade statistics.

Information on energy inputs into production differs significantly over time and between different products. In some countries like Sweden industrial statistics provide annual data from 1911 onwards with information about energy use for all the subsectors of manufacturing.[7] In other cases benchmark industrial censuses exist (e.g. the Census of Production beginning in 1907 in Britain; In Germany the first complete industrial census was in 1936, with more limited censuses from 1875). In the 19th century data is less easily available, but the industrial structure was also relatively simpler with fewer products and large groups with relatively homogeneous characteristics. Even in the absence of formal industrial censuses, there are occasional comprehensive surveys of fuel consumption in sectors of industry and/or the employment of steam power (such as the Royal Commission on Coal of 1870 in the UK (HMSO- Her Majesty's Stationery Office, 1871), or the Inquérito Industrial de 1881 in Portugal (MOPCI-Ministério das Obras Públicas, Comércio e Indústria, 1881)).

The multipliers have been constructed for benchmark dates (ca. 1870, 1913 and 1935). As detailed in the SI, we have country-specific multipliers for most goods, but where data is lacking we assume constant energy efficiency across countries in identical traded goods as a most plausible assumption (and one widely employed in modern studies). In most countries this effects only a very small proportion or none of our data. In Germany and Italy technical efficiencies could not be established for a much larger proportion of goods. Where necessary we assume the same production technologies for an appropriate comparator, equating for example coal-rich Germany and Britain.

3.2. Calculating Energy Embodied in Trade

The next step is to apply the multipliers to the trade statistics and calculate the embodied energy flows in international trade. We have used national trade statistics for each country. We have avoided currency problems by always using the trade statistics expressed in tons rather than monetary values. Thus we adjust the energy flows embodied in trade based on the physical quantities of traded commodities and the

[7] A difference between the method of process analysis that we follow here and that of some contemporary input-output methods is that we only capture the direct energy used in different process steps. This means that while contemporary consumption based accounts try to apportion energy used for commercial transportation to the different relevant sectors, we do not. This would be desirable in a complete accounting but current data availability does not permit this.

respective energy demands in their production.[8] To use the physical quantities of traded goods, rather than the values, is fairly unproblematic for this early period. The bulk of traded goods in this period were relatively standard commodities such as iron, grain or cotton, but this method becomes more troublesome for more complex goods like machinery and vehicles. Where weight was not reported we had to make assumptions about the average relation between weight and value, based on sources described in the SI. It is important to note explicitly that our data does take into account imported goods that were used as inputs for domestic processes for the production of goods then exported. In this early stage of global trade these kinds of trade flows were not as significant as they are today, but mattered in for example the case of raw cotton imported into Britain that was used to produce British textiles for export.

3.3. Adjusting Energy Intensity

In the last step we use the net value of energy embodied in trade (NEE). This is written according to the conventions of trade analysis:

$$\text{NEE} = \text{Exported energy} - \text{Imported energy}.$$

This value is then inserted into the following equation:

$$\text{CBA} = \text{PBA} - (\text{NEE})$$

used to calculate energy with a consumption-based approach (CBA) by adjusting the Production Based Approach (PBA). Thus if imports are larger than exports, the subtraction of a negative value of the NEE will make the CBA larger than the PBA, while in the reverse case of exports exceeding imports, this will give a positive value of the NEE, making the CBA smaller than the PBA. The adjusted CBA is then used to calculate a new consumption-based energy intensity for each country and the aggregate sample.

Obviously there is a direct link between the amounts of energy consumed within the borders of a nation, and the same nation's GDP. Energy has been used to fuel the furnaces and engines of that nation in a very direct sense. Energy used in production and services increased GDP. When we establish energy intensity from the consumption-based perspective instead we lose some of that straightforward connection. Some of the energy used within a country's borders is for producing exports, which contribute to the national income. When we adjust for energy flows embodied in both imports and exports there is no longer the direct logical link to national income. Strictly speaking the monetary flows must still balance, in that the income spent on imports must balance that earned by exports, net of capital transfers. But the implicit assumption behind a consumption-based energy intensity is that income per capita would not be much affected by the composition of exports, a counterfactual scenario that is very difficult to assess. Nevertheless we regard the adjusted energy intensity as an interesting indicator of the energy demands of consumption at particular income levels, and one less influenced by the vagaries of local resource endowments and international specialization. Furthermore, we are interested in how consumption-based energy intensity changes during industrialization, rather than its level in relation to production-based energy intensity, and for that purpose our approach helps understand the effect from trade on energy demand and intensity.

[8] Unlike input-output analyses that rely on calculating embodied energy using the value of trade, we use purely physical indicators, so export prices are not part of our calculations and therefore do not affect the results. Of course export incomes are part of GDP and the denominator of energy intensity irrespective of whether this is measured from the production or consumption side.

4. Results

4.1. Energy Embodied in the Traded Goods

The goods that mattered most for energy embodied in trade differ among our countries and between dates. Fig. 4 shows the composition of net embodied energy in trade for the major product groups in three benchmark years – 1870, 1913 (1907 for the Great Britain) and 1935. We provide corresponding more detailed tables for all countries in the SI with full export and import accounts. Fig. 4 shows the final net energy balance for major commodities only.

As seen in Fig. 4, Britain was a large net-exporter of capital goods, like iron and steel, throughout the period 1870–1935. It was also a significant net-exporter of cotton textiles and importer of raw cotton around 1870, and in 1907, but in 1935 the importance of raw cotton imports had dwindled, although textile exports were still significant. Energy embodied in grain imports (mainly fodder for the draft animals used to grow the grain) steadily rose over time. Britain exported large amounts of coal and coke. While the amount of energy embodied in the export of fuels (i.e. consumed in mining and coke production) was obviously only a fraction of its entire energy content, its embodied energy alone was still significant enough to make them the third ranked commodity group for embodied energy in 1907, and fifth in 1935.

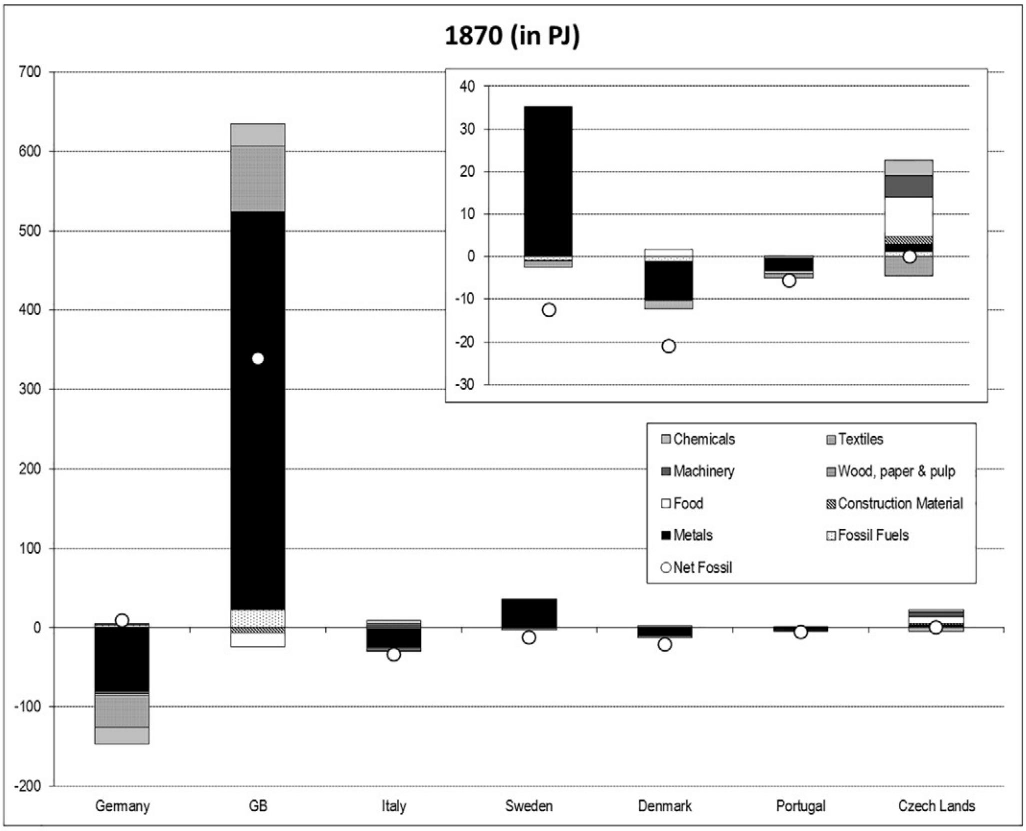
It is important to note that we do not include the direct energy content in coal and coke that will be burned elsewhere as part of embodied energy, but for comparative purposes we report on the actual magnitude of the direct energy of fossil fuels with a separate mark in the graphs in Fig. 4 for all countries (white dot titled 'net fossils'). This comparison provides an interesting perspective on the amount of embodied energy and direct energy content of traded fossil fuels. In 1870, for example, the net direct energy content of British coal exports was dwarfed by the magnitude of the embodied energy in the exported metals. By 1913, however, with the ongoing rise of fossil fuel exports from the Great Britain, the energy balance shows a different picture.

Germany became a large net-exporter of heavy industrial capital goods during the period studied with a peak in 1913. As Table 1 shows, in in the early 1870s Germany was a net importer of embodied energy, mainly iron and steel goods. By 1913, however, the country became a major exporter of iron and steel, machinery and chemical products while primarily importing agricultural goods.

Embodied energy in coal and coke (the energy used to extract and produce those fuels), as in other coal-rich countries in our sample, also made up a large fraction of exported embodied energy. Contrary to Britain, Germany never had substantial textile exports, but did have a large chemical sector. Again, a full energy accounting of German trade would have been much larger, since the direct energy content of coal and coke exports are not included in the measure of embodied energy.

For the remaining countries the embodied energy in trade differed substantially, both in terms of magnitude but also in the composition of major traded goods. Both Sweden and the coal-rich Czech lands were net exporters of embodied energy throughout the period of study. Initially in Sweden a large share of embodied energy in exports was concentrated into one sector – metals, but by the end of 1935, paper and pulp became the largest product group. In the Czech lands, on the other hand, the composition of energy embodied in goods was far more fragmented among a variety of consumer goods, such as textiles, sugar and glass, but also metals, which later became the largest export group.

Italy, Denmark and Portugal, on the other hand remained net importers of embodied energy throughout the period of study. In all three countries imports of coal, coke and steel products were important, while on the export side Italy had largest shares of embodied energy in textile products and Denmark and Portugal in food products. In terms of direct energy content of traded fossil fuels (net fossils), all countries without domestic coal reserves (Italy, Portugal, Sweden and Denmark) were clear net importers.



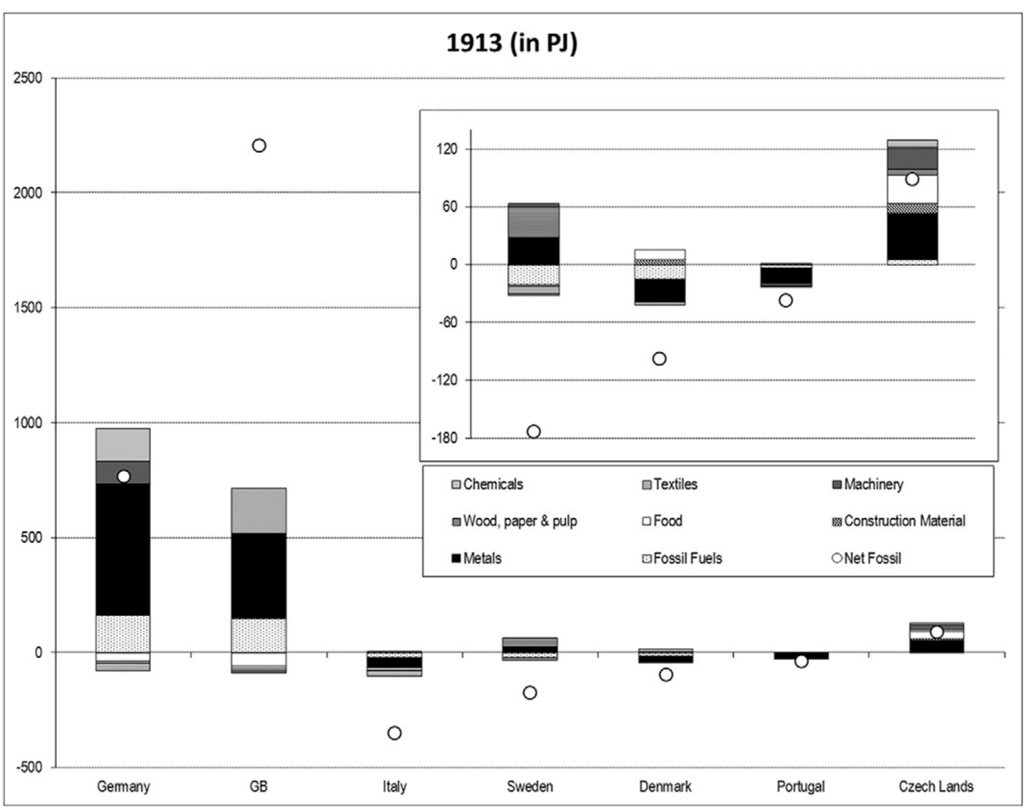


Fig. 4. Energy embodied in trade by major products, 1870–1935. Note: Positive values denote net exports and negative values are net imports. Values only include energy embodied in traded goods but not the actual direct energy content of the traded goods. The white dot shows the actual energy content of the traded fossil fuels; positive values denotes net exports of fossil fuels and negative values denotes net imports.

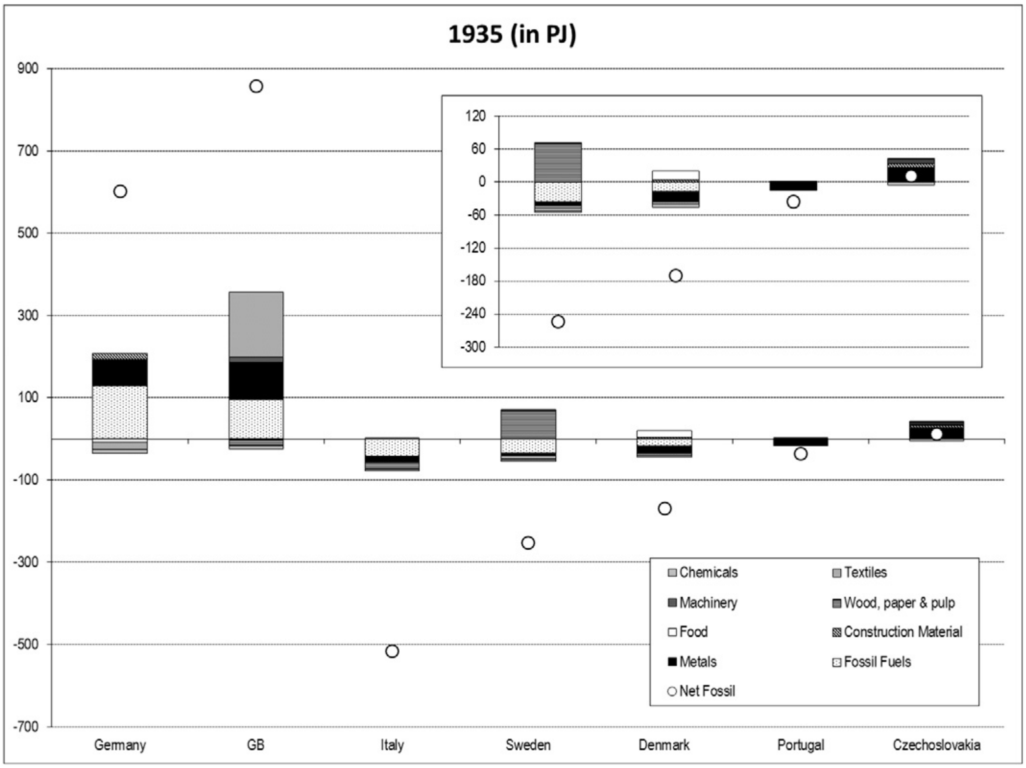


Fig. 4 (*continued*).

4.2. Adjusted Energy Intensity

By aggregating the results for our whole sample we can study the net-balance of energy embodied in trade for a group of significant European countries, but not for western and central Europe as a whole. Germany and the Czech lands were also exporters to countries further east within Europe. The overall results are provided in Tables 1 and 2. The main conclusion is that when energy embodied in trade is accounted for, energy intensity changed substantially, not only for individual countries but also for our whole sample.

The inverted U-curve of German energy intensity became much less pronounced after trade adjustment. This was not only due to internal flows of embodied energy within our sample, as aggregate curve also becomes flatter over the late 19th and early 20th century. It goes up a small amount (13%) between 1870 and 1913. For Britain the curve becomes flat right across the second half of the 19th century.

One might hypothesize that some of the non-coal economies that did not have any inverted U-shape curve from the production-based account might have one with the consumption-based method. But as Table 1 clearly demonstrates this did not happen. The main net-flows of energy were not between the countries of our sample. Instead there was a net outflow of energy to other parts of the world.

4.3. German, British and Czech Trade Patterns

In the late 19th century, only Britain had a large amount of trade with non-European countries (in monetary values), about half of its total. The USA and India were the main non-European trading partners for the UK, with Canada, Argentina, Australia and Russia making up about 5% each. In the period of our analysis Germany and the Czech lands are the most interesting cases from an energy intensity point of view, because after 1870 they are the only countries driving the curve of energy intensity up. As we have seen, in Germany's case this had a clear inverted-U form before adjustment for trade, and it moved from being a net-importer of embodied energy in 1870 to a net-exporter by 1913. Thus at least part of the increase in national energy consumption to 1913 must have been satisfying consumers in other countries.

We have seen the drastic change in Germany's energy intensity curve when adjusted for trade. The country mainly responsible for the inverted U-shaped curve of energy intensity at a European level in this period had a much smaller rise in energy intensity when viewed from the consumption side. Even though aggregate intensity might rise by Germany cornering a larger share of continental output this effect was not large enough in our sample to offset the reduction from accounting for energy embodied in trade.

It thus becomes of particular interest to identify Germany's trading partners. If their energy embodied in exported goods largely left Europe, we could conclude that intercontinental trade was the main factor driving up the non-adjusted curve for the continent. However, Germany's main trading partners were Austria-Hungary, France, Russia and the UK. Unlike Britain, its trade was not orientated outside the continent. Of these countries France is not in our sample and Austria-Hungary is only partially covered (the Czech lands being part of it). In sheer economic (value) terms Germany always had a favourable balance of trade in relation to the UK, but a negative balance in relation to their main non-European trading partners, the USA and Russia. Germany's exports of goods with a large share of embodied energy, such as iron and steel, and coal and coke, were also mostly to European neighbours, as shown in Table 3. Substantial amounts went to countries outside of our sample, such as France, Belgium and the Netherlands.

The Czech lands also represent an interesting case, although the share of their trade within the sample is small relative to Britain and Germany. Before the establishment of Czechoslovakia in 1918, the Czech lands were part of the Austro-Hungarian Monarchy. Austria-Hungary was to a large extent a “self-sufficient economic entity” (Matis, 1994). The composition of goods in Czechoslovak foreign trade was relatively stable throughout the period of study, with imports dominated by raw materials and commodities, while consumer and industrial goods formed the largest share of exports. In the early stages of the

Table 1
Production based (PB) energy, consumption based (CB) energy and PB energy intensity (PB E/Y) and CB energy intensity (CB E/Y) for all our seven countries and the aggregate group.

	1832	1849	c.1870	c.1913	1935
Energy, PB (PJ)		**2842**	**5196**	**14,204**	**13,371**
Denmark		34	44	124	200
Germany		481	1360[a]	6227	5381
Italy		326	353	688	883
Portugal		54	66	116	136
GB	979	1711	3004	6114	5738
Sweden		149	190	340	410
Czech		87	179	595	623
Energy, CB (PJ)			**4760**	**12,403**	**12,963**
Denmark			58	157	238
Germany			1503[a]	5252	5111
Italy			371	781	958
Portugal			71	139	151
GB	959	1535	2441	5311	5539
Sweden			157	311	393
Czech		86[a]	159	452	573
GDP (bn 1990 $)			**240.1**	**587.7**	**770**
Denmark			4.1	11.7	20.2
Germany			76.7[a]	237.3	275.5
Italy			43.5	96.9	137.4
Portugal			4.3	7.2	11.6
GB	35.9	54.2	93.3	191	262
Sweden			5.1	16.2	28.1
Czech		6.8[a]	12.6	27.4	34.8
PB E/Y (MJ/$)			**21.7**	**24.0**	**17.0**
Denmark			10.6	10.6	9.9
Germany			17.7	26.2	19.5
Italy			8.1	7.1	6.4
Portugal			15.2	16.1	11.8
GB	27	31.6	32.2	32.0	21.9
Sweden			33.9	22.2	14.9
Czech		12.8[a]	14.3	21.7	17.9
CB E/Y (MJ/$)			**19.8**	**21.1**	**16.8**
Denmark			14.1	13.5	11.8
Germany			19.6	22.1	18.6
Italy			8.5	8.1	7.0
Portugal			16.3	19.3	13.0
GB	26.4	28.1	26.1	27.8	21.1
Sweden			28.0	19.2	14.0
Czech		12.7	12.7	16.5	16.3

Note: PB and CB are both net of trade (Exports minus imports), but in the case of PB it is only direct energy content of carriers like fossil fuels (coal and oil), and in the case of CB it is also the net embodied energy in trade. Text in bold is total for seven countries. PJ $= 10^{15}$ J.

[a] Czech '1849' data is for 1841. Danish data is for 1874. German data is for 1872.

Table 2
Production based (PB) energy intensity, and consumption based (CB) energy intensity, index 1870 = 100.

	1832	1849	c.1870	c.1913	1935	Pattern
PB energy intensity						
Denmark			100	100	93	No inverted U
Germany			100	148	110	Inverted U
Italy			100	88	79	No inverted U
Portugal			100	106	78	Tiny inverted U
GB	85	98	100	99	68	Long run inverted U, but very flat 1849–1913
Sweden			100	62	43	No inverted U
Czech			100	152	125	Inverted U
7 countries			100	112	80	Inverted U
CB energy intensity						
Denmark			100	96	84	No inverted U
Germany			100	113	89	Shallow inverted U
Italy			100	95	82	No inverted U
Portugal			100	118	80	Inverted U
GB	101	107	100	107	81	No inverted U
Sweden			100	69	50	No inverted U
Czech			100	130	129	Upword slope then flat
7 countries			100	107	85	Shallow inverted U

industrial development in Czechoslovakia, textile and glass products accounted for the largest export share by value. In volume terms, the Czech lands have historically been a major exporter of coal (brown coal) and wood, most of which was destined for the current territory of Austria. Exports going west from Czechoslovakia consisted mainly of sugar, timber, glassware, wooden articles, paper and hops. Exports eastwards from Czechoslovakia (including the territory of Austria) were dominated by iron and steel, machinery, chemical products, sugar, alcohol, textiles and footwear (Cisar and Pokorny, 1922). By 1913 the Czechoslovak territories were the most important trading region of the whole monarchy, and within it played a similar role to Germany in a larger European context, or Britain in regard to a variety of trading partners earlier in the 19th. By 1913 some 70% of total Czechoslovak production was destined for exports, mainly within the borders of Austria-Hungary, with only some 30% estimated to be consumed domestically.

4.4. Consumption-Based National Energy Accounts

National energy histories change substantially when viewed on a consumption basis. Accounting for trade brings major adjustments to levels as well as trends (see Table 4). However, unsurprisingly, the impact is rather different in magnitude and direction. Measured by dividing embodied energy in trade by production-based national energy consumption (where a positive sign indicates export of energy and a negative sign import) embodied energy in trade varies between +24% (Czech lands in 1913) and −31% (Denmark in 1870). Net exporters are the coal-rich countries; Britain and the Czech lands, but also Sweden, rich in charcoal and iron ore. Coal-rich Germany is a very interesting case; it moves from being a net-importer in 1870 (−11%) to a net–exporter in 1913 (+16%) and continues to be a net-exporter in 1935 (+4%). Net importers are Denmark, Portugal and Italy. These are countries that lacked domestic coal resources, and were not well-endowed with iron ore.

In all cases the net adjustment was smaller in 1935 than 1913, reflecting the interwar era of protectionism and Depression. In Sweden, Britain and Denmark the relative size of traded embodied energy declined after 1870. In fact Sweden and Britain are surprisingly similar in the ratios and trends of net-exported energy at the three benchmarks; it seems the comparative advantages of energy-intensive production fell for these two countries over time. This is not surprising given dramatically falling transportation costs, which helped equalize energy costs internationally. Land-locked Germany came later to exploiting its coal-advantages, with a peak share of embodied energy in exports in 1913.

In Portugal and the Czech lands the gap between consumption- and production-based was largest in 1913 and declined thereafter, as volumes of trade diminished. Portugal was a late industrializer, and late in importing steel and coal and machinery, so this is expected. The Czech lands could, to some degree, also be characterized as a late industrializer, though the nature of the country's trade pattern and domestic production changed substantially between 1870 and 1913. In fact, by the beginning of WWI the territories of the Czech lands covered the needs of the whole Austrio-Hungarian Monarchy, and at this point its pattern of trade in 1913 thus resembled that of other industrialized countries, dominated by imports of raw materials and exports of manufactured goods.

5. Conclusions

This study shows that applying the consumption-based approach rather than the production-based account is relevant for analysing Europe's intensive phase of industrialization, 1870–1935. The inverted U-shape curve for energy intensity is greatly diminished for our set of seven European countries when we account for energy embodied in

Table 3
Share of German exports of iron and steel goods, coal and coke to main trading partners, 1913.

Tons/country	Pig iron (782,911)	Cast iron (700,779)	Iron goods (1,173,265)	Coal (34,598,408)	Coke (6,432,986)
UK		71%	22%		
France	15%			9%	37%
Belgium	40%	10%		17%	15%
Netherlands			14%	21%	
Austria-Hungary	14%	6%		35%	16%
Japan			8%		
Argentina			8%		
Russia				6%	8%
Switzerland					6%

internationally traded commodities. Instead we find a much flatter curve for the 19th century and then a declining curve from WWI onwards, with the rise between 1870 and 1913 falling by around two-fifths.

The results show that the coal-rich countries were making use of their coal resources and specializing in heavy industrial production, some of it for export to other European countries that lacked domestic coal resources. The role of coal for specialization peaked before the WWI and diminished thereafter. This is especially obvious in the case of Germany that net-exported around 16% of national energy consumption in embodied form before the War. This substantially affected the energy intensity pattern for Germany and our set of seven countries. Britain's proportional net-export of energy peaked at an early date, around 1870, when 19% of energy consumption was embodied in exports, a similar level to China today (Tang et al., 2016).

However, Europe is larger than our set of seven countries, and more than half of Germany's export of heavy industrial goods went to other European countries outside of our sample. Thus for the entirety of Europé it is highly unlikely that the curve disappears, as Britain and Germany were the main industrial producers.

These results shed new light on the historical relationship between energy and GDP. The stylized fact of the inverted U-shape curve for energy intensity suggests that during an intense phase of industrialization, energy use in relation to GDP, by necessity goes up. This is because of structural change, with a growing share of industry in GDP, even if within-sector energy intensity is falling. Previous research has shown that

Table 4
Individual country patterns.

	Imported fossil fuels, PJ	Total national energy consumption, minus food, PJ	Embodied in imports, PJ, (within brackets; of which coal and coke)	Embodied in exports, PJ	Net national energy consumption	Net-exported energy embodied in goods, PJ	Net exports/national energy, %
Great Britain							
1832		979	23	43	959	20	2%
1849		1712	41	218(5)	1535	177	10%
1870	0.85	3004	94	657(21)	2441	563	19%
1907	31	6114	291	1094(148)	5311	803	13%
1935	322	5738	224	423(73)	5539	199	3%
Germany							
1872	105	1360	279 (7)	143 (11)	1503	−143	−11%
1913	271	6227	302 (15)	1278 (17)	5252	976	16%
1935	201	5381	178 (24)	448 (153)	5111	270	4%
Czech Lands							
1841	0	87	0.9	1.8	86	0.95	1.1%
1870	0	179	8	28 (1.1)	160	20	11%
1913	0[a]	596	20	163 (4.9)	452	142	24%
1935	59[b]	623	34	85 (6.9)	573	51	8.1%
Sweden							
1870	12.5[c]	190	8 (0.8)	41	157	33	17%
1913	173	340	57.5 (20.9)	87	311	29.5	9%
1935	253	410	72 (36)	89	393	17	4%
Denmark							
1870	21	44	16 (1)	3	57	−13	−31%
1913	98	124	60 (9)	24	158	−33	−27%
1935	170	200	71 (18)	32	238	−38	−19%
Portugal							
1870	5.6	66	5.8 (0.3)	0.7	71	−5.0	−8%
1913	37.2	116	27.5 (3.1)	4.2	139	−23.3	−20%
1935	36.2	136	18.9 (1.7)	4.4	151	−14.4	−11%
Italy							
1870	34	353	28 (1,8)	10	371	−18	−5%
1913	352	688	130 (19)	36	781	−94	−14%
1935	516	883	112 (38)	37	958	−75	−8%

[a] 89 exported.
[b] 70 exported.
[c] Of coal 12.3 PJ or (93%) was imported. All oil (0.2 PJ) was imported in 1870.

for European countries this was not the case, and energy intensity was flat or falling during industrialization (Gales et al., 2007).[9] The current study reinforces this revised view and suggests that a flat or declining energy intensity during industrialization is a normal feature, found also in some coal-rich early industrializers, if counted net of energy embodied in international trade. The higher incomes from industrialization do not necessarily, or even normally, lead to higher energy intensity in a consumption-based approach.

As coal was the dominant fuel in this period, these results suggest that early industrializers bore a large domestic environmental burden to the benefit of later industrialisers and less coal-rich countries who imported capital goods and fuel, both inside and outside Europe. Britain and Germany and the Czech lands gave others the means to industrialize and develop, and suffered pollution and health problems as a consequence (of course, it is well documented that their imports in turn may have been associated with other problems). This complicates the way we perceive the role of core and periphery in economic development. This empirical result by no means overturns or reverses all earlier propositions but suggests the environmental, economic and social impact of trade is a complex area. Such data also potentially speaks to ethical debates on current responsibility of nations for historical fossil fuel emissions. It is clear that production- and consumption-based approaches will give different results, in the past as well as the present. The data may also help shed light on different countries' roles in the world trade system, particularly when we can refine studies to examine trade and embodied energy in particular kinds of goods (such as capital goods associated with phases of infrastructural development, as well as consumer goods). The results stress how important it is to analyse energy and emissions embodied in international trade for assessing nations' performance in complying with production-based emission targets in the present and future, and by doing so actually reduce global carbon emissions and pollution, rather than displacing them elsewhere in the world system.

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Appendix A. Supplementary data

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[9] Obviously environmental burden is not proportional to energy per se. Certain energy carriers cause more pollution than others.

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